International Workshop "Shapes and Dynamics of Atomic Nuclei: Contemporary Aspects" (SDANCA-15)
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Description of Shape Transitions in Superheavy Nuclei within Covariant Density Functional Theory

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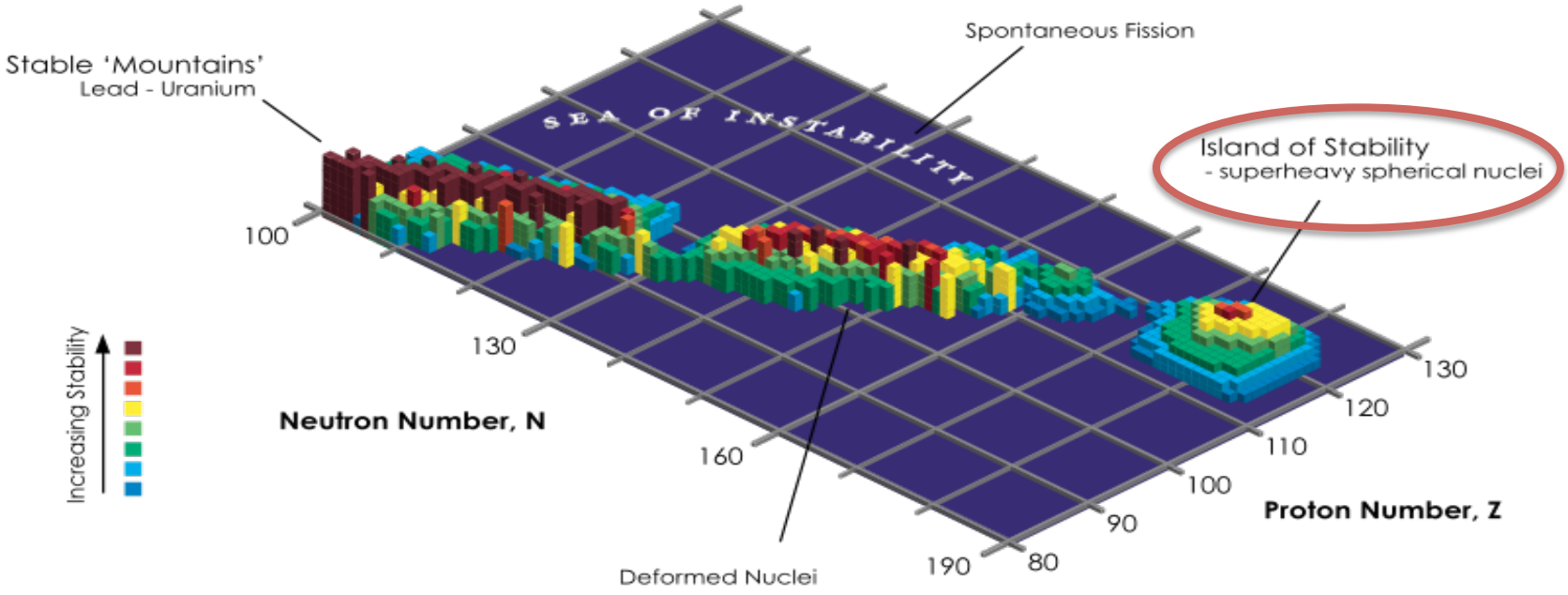
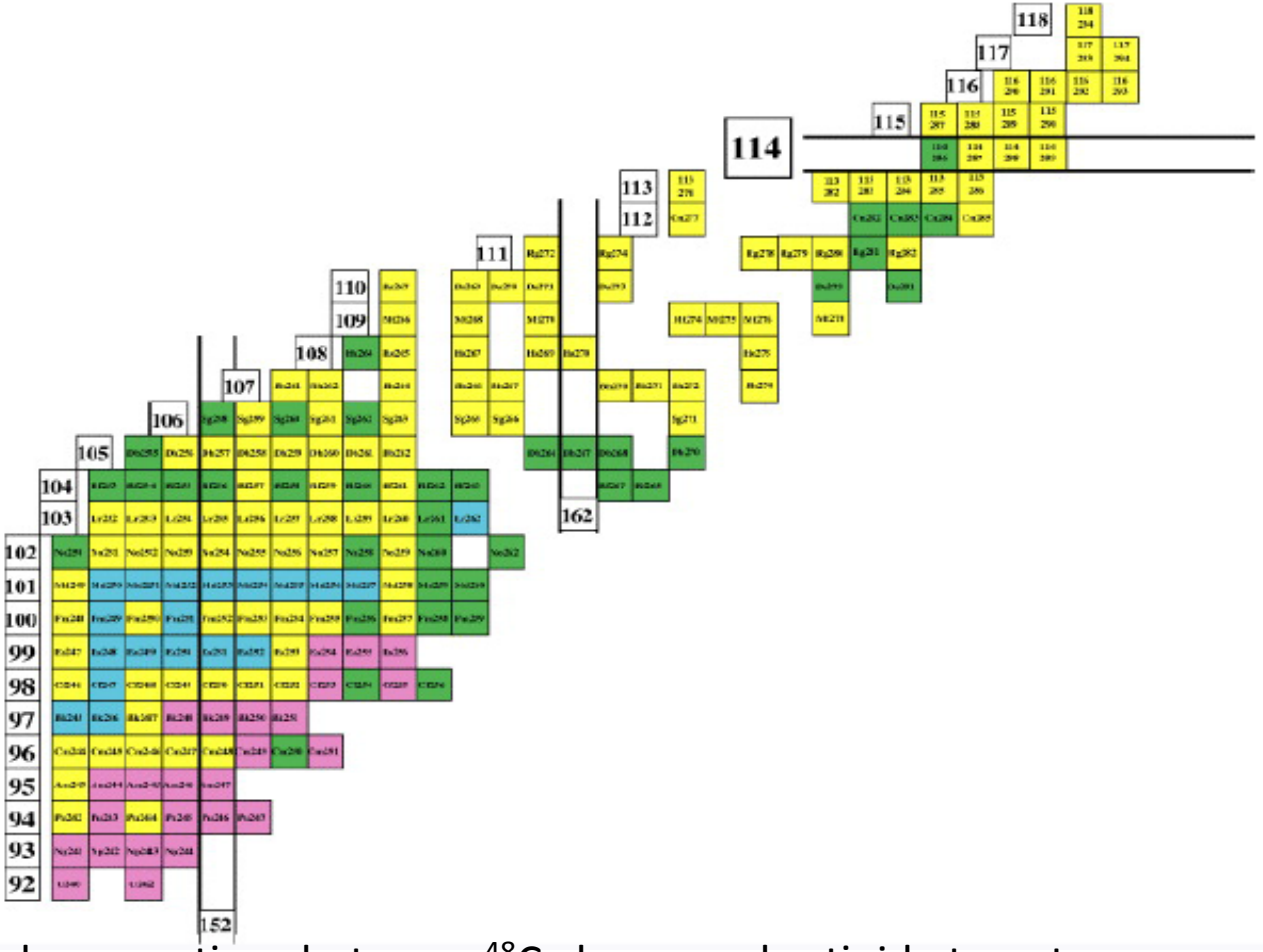
Motivation-Theoretical aspects



- Elements with atomic number greater than Uranium (Z=92) exist due to shell effects. Balance between nuclear force and coulomb field.
- Prediction of an island of stability around Z=114 and N=184 in the 1960's.
- Theoretical studies were based on the traditional *macroscopic-microscopic* approach for many years. Since the late 1990s SCMF based on *the Gogny interaction, the Skyrme energy functional, and the relativistic meson exchange effective Lagrangians* have systematically been applied to the structure of SHN.
- Models predict rapid shape transitions.

Motivation-Experimental status



- Compound nucleus reactions between ^{48}Ca beam and actinide targets
- New elements with Z=113-118 have been synthesizes and new isotopes of Ds (Z=110) and Cn (Z=112) have been identified.
- Decay energies and half-lives provide evidence of a significant increase of stability with increasing neutron number in the region of SHN.

Relativistic Energy Density Functionals

Why choose a relativistic formulation of the nuclear many-body problem?

- The Dirac equation provides an economical and natural description of bulk nuclear properties and the nucleon single-particle spectrum, with the correct spin-orbit force arising automatically.

- Kinematical relativistic effects are small in nuclei, but the different behavior of the large Lorentz scalar and vector potentials leads to large dynamical relativistic interaction effects in the nuclear matter energy density (natural saturation mechanism!)

- A covariant formulation in terms of hadron degrees of freedom incorporates the basic symmetries of QCD (Lorentz invariance, parity conservation, isospin symmetry, spontaneously broken chiral symmetry).

- The self-consistent relativistic mean-field framework presents a particular realization of the relativistic Kohn-Sham density functional theory.

Relativistic Energy Density Functionals

EDF's provide an accurate description of ground-state properties and collective excitations over the whole nuclide chart.

Relativistic Energy Functionals

The elementary building blocks of the point-coupling vertices are two-fermion terms of the general type:

$$(\bar{\psi}\mathcal{O}_\tau\Gamma\psi) \qquad \mathcal{O}_\tau \in \{1, \tau_i\} \qquad \Gamma \in \{1, \gamma_\mu, \gamma_5, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$

10 building blocks characterized by their transformation character in isospin and in spacetime.

Relativistic Hartree-Bogoliugov framework

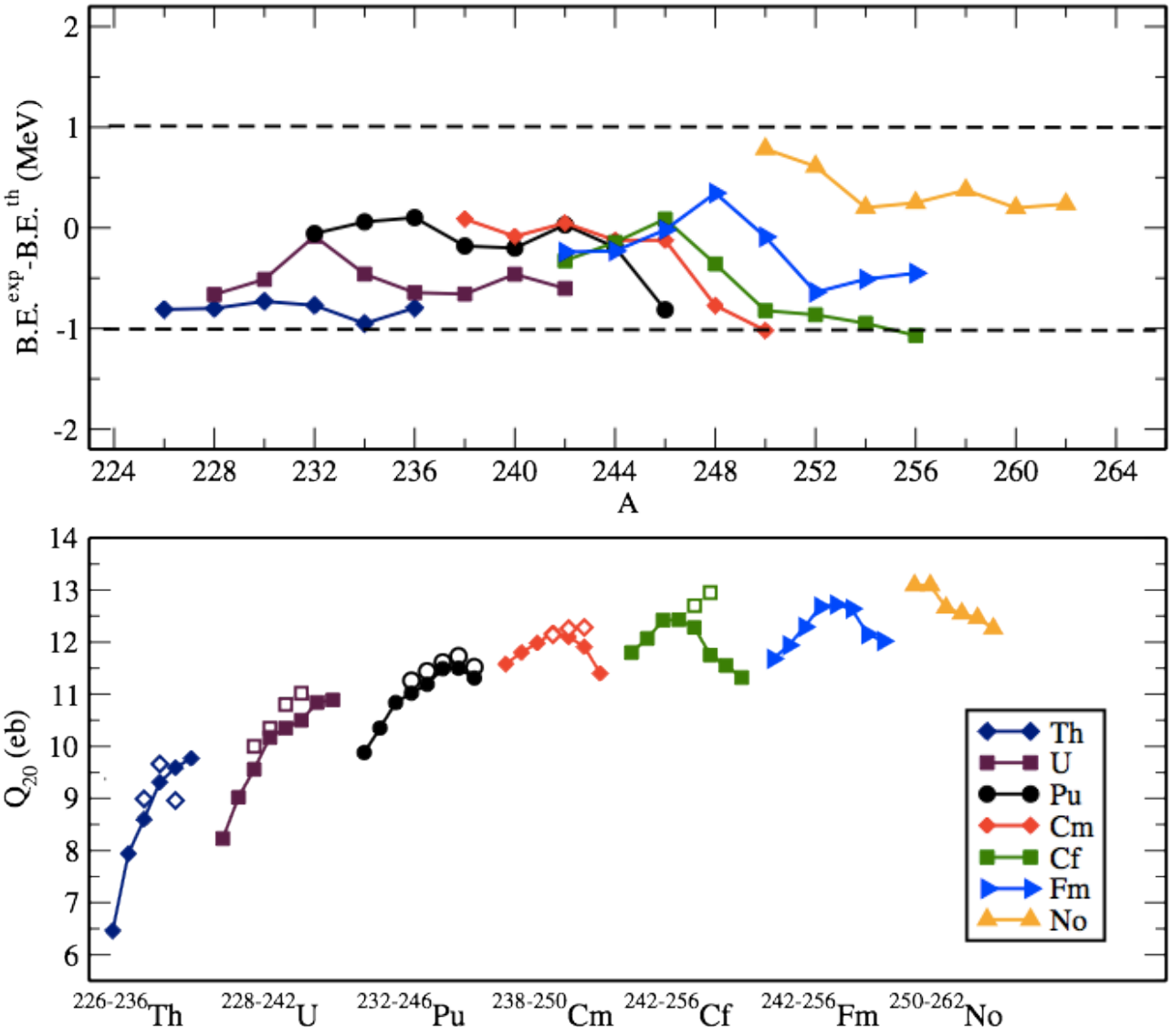
Unified treatment of the nuclear MF (particle-hole (ph)) and pairing (particle-particle (pp)) correlations

$$E = E_{RMF}\,[j_\mu, \rho_s] + E_{pp}(\kappa,\kappa^*)$$

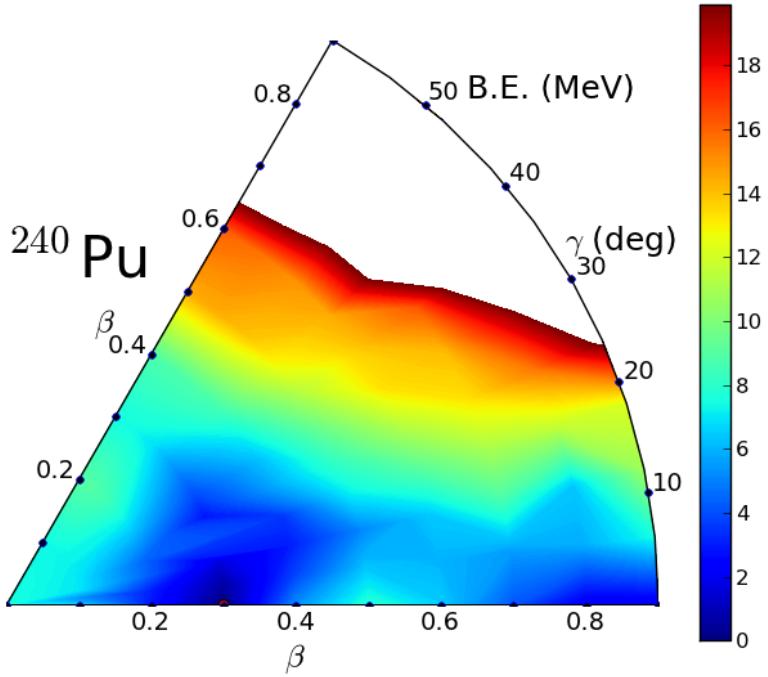
DD-PC1 functional tted to the experimental masses of 64 axially deformed nuclei in the regions A≈ 150 -180 and 230 -250.

Pairing interaction: finite range separable pairing

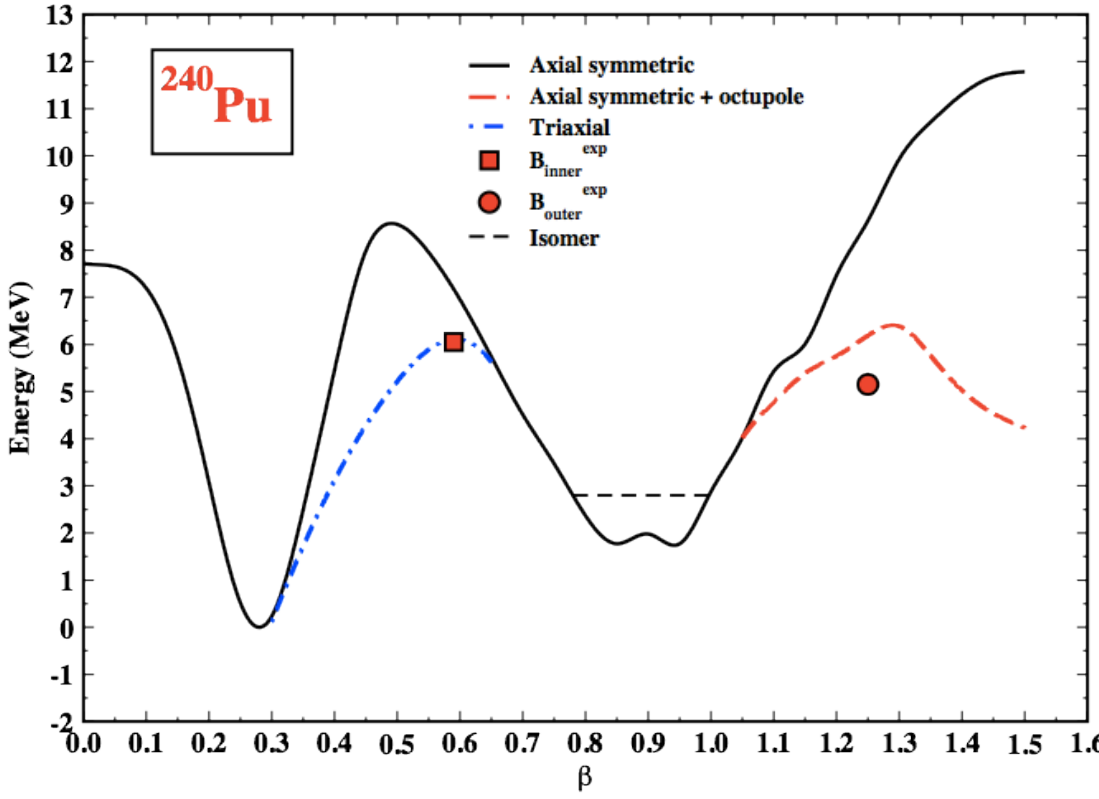
Predictive power of the model: Ground-state properties of actinides



Predictive power of the model: "Double-humped" fission barriers of actinides



ND and SD minima are separated by the barrier.



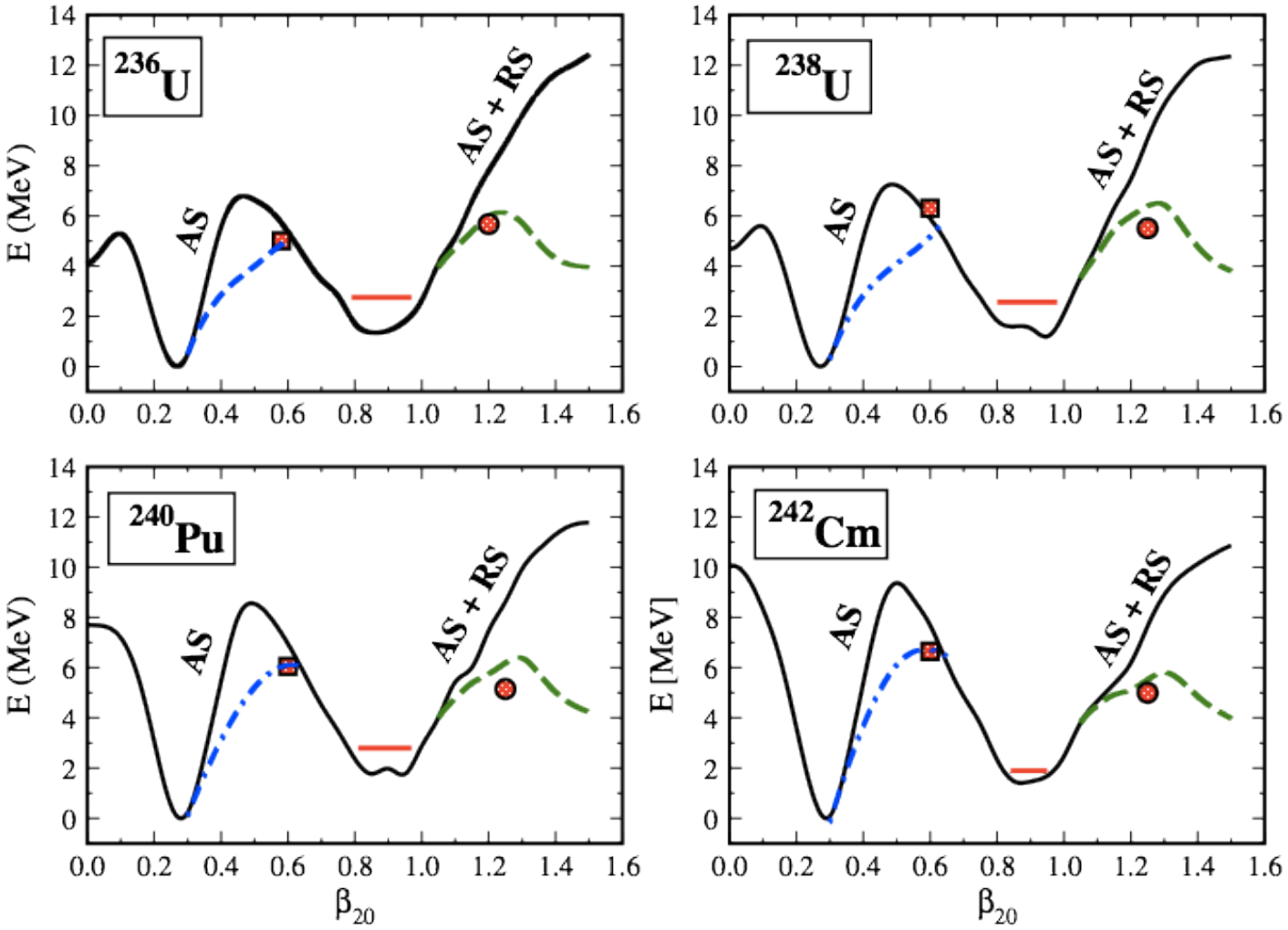
Triaxial effects: lower the inner barrier.
Reflection asymmetry (octupole) lower the outer barrier.

Potential energy surfaces of actinides

Black: Axial symmetric calculations.

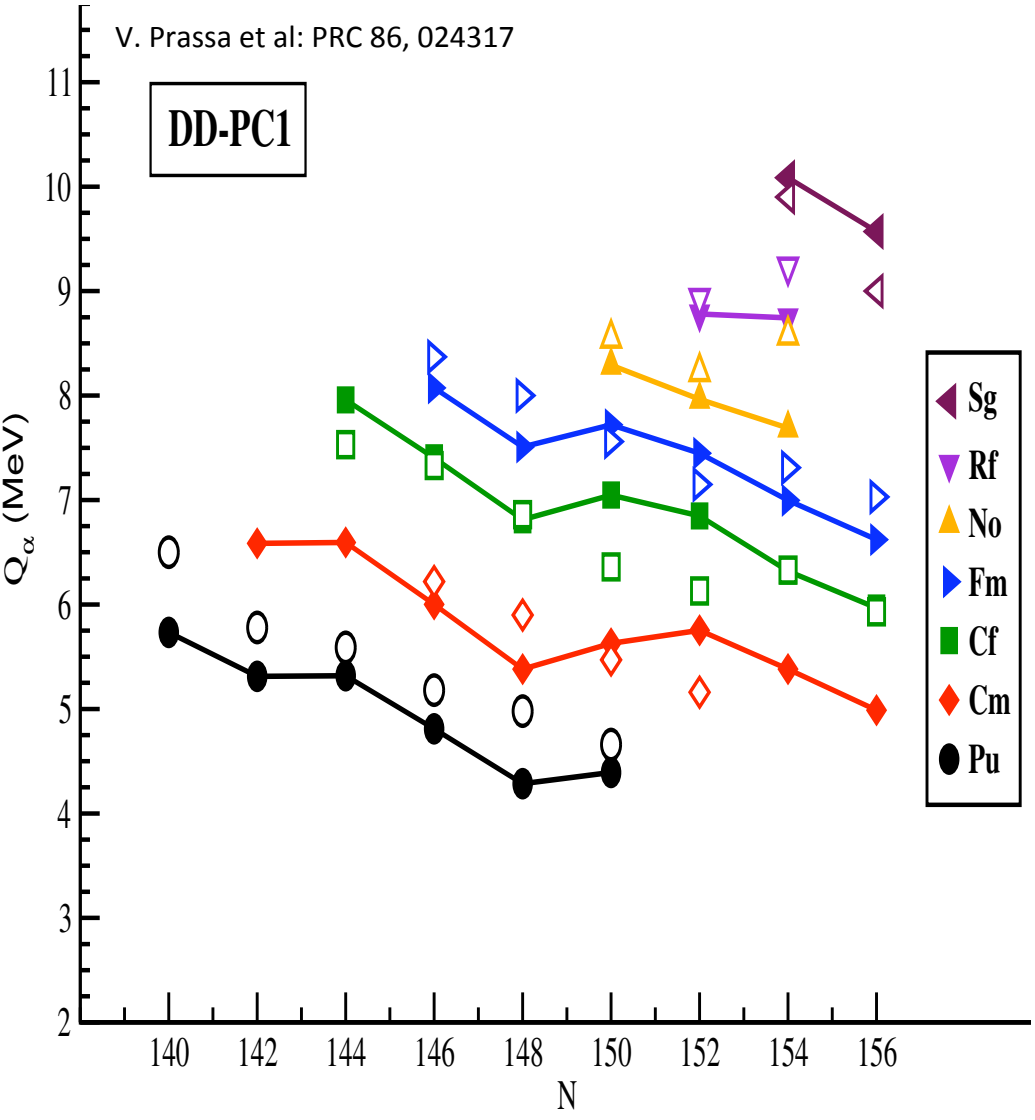
Blue: Triaxial calculations. Decrease of the first barrier.

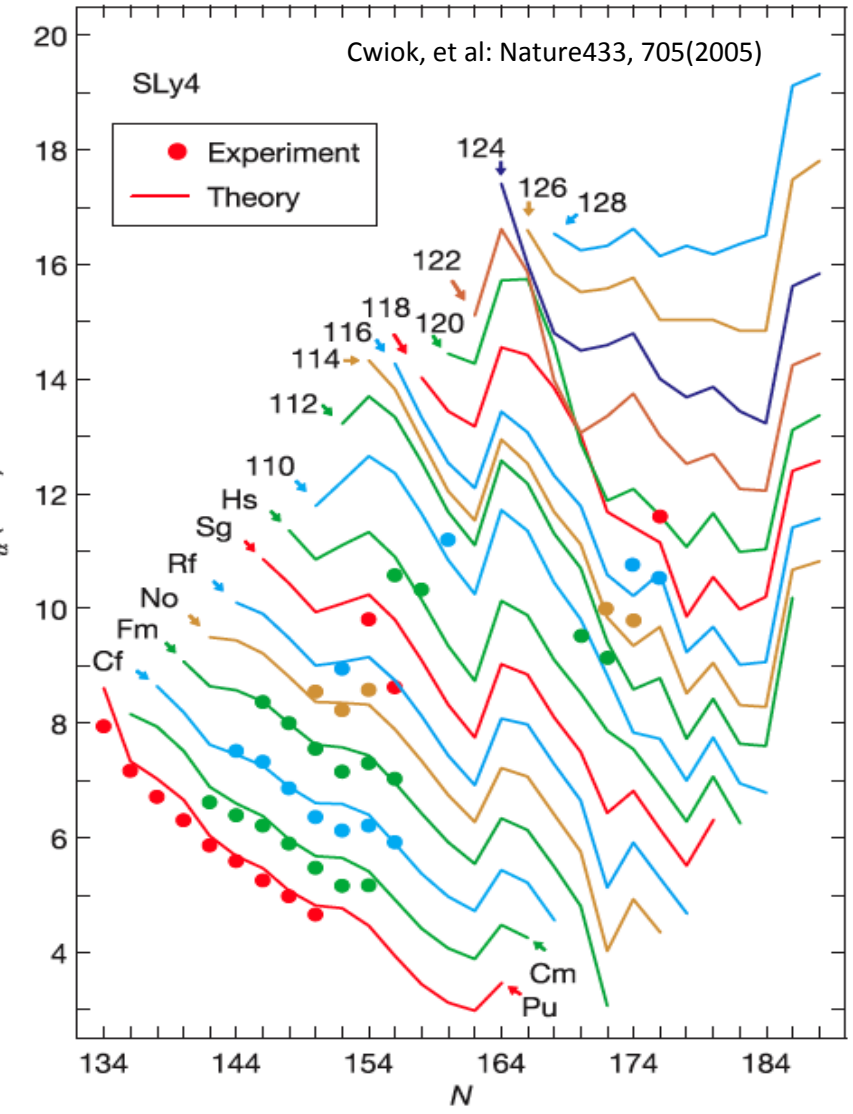
Green: Axial symmetric calculations including reflection asymmetry (octupole). Decrease of the second barrier.



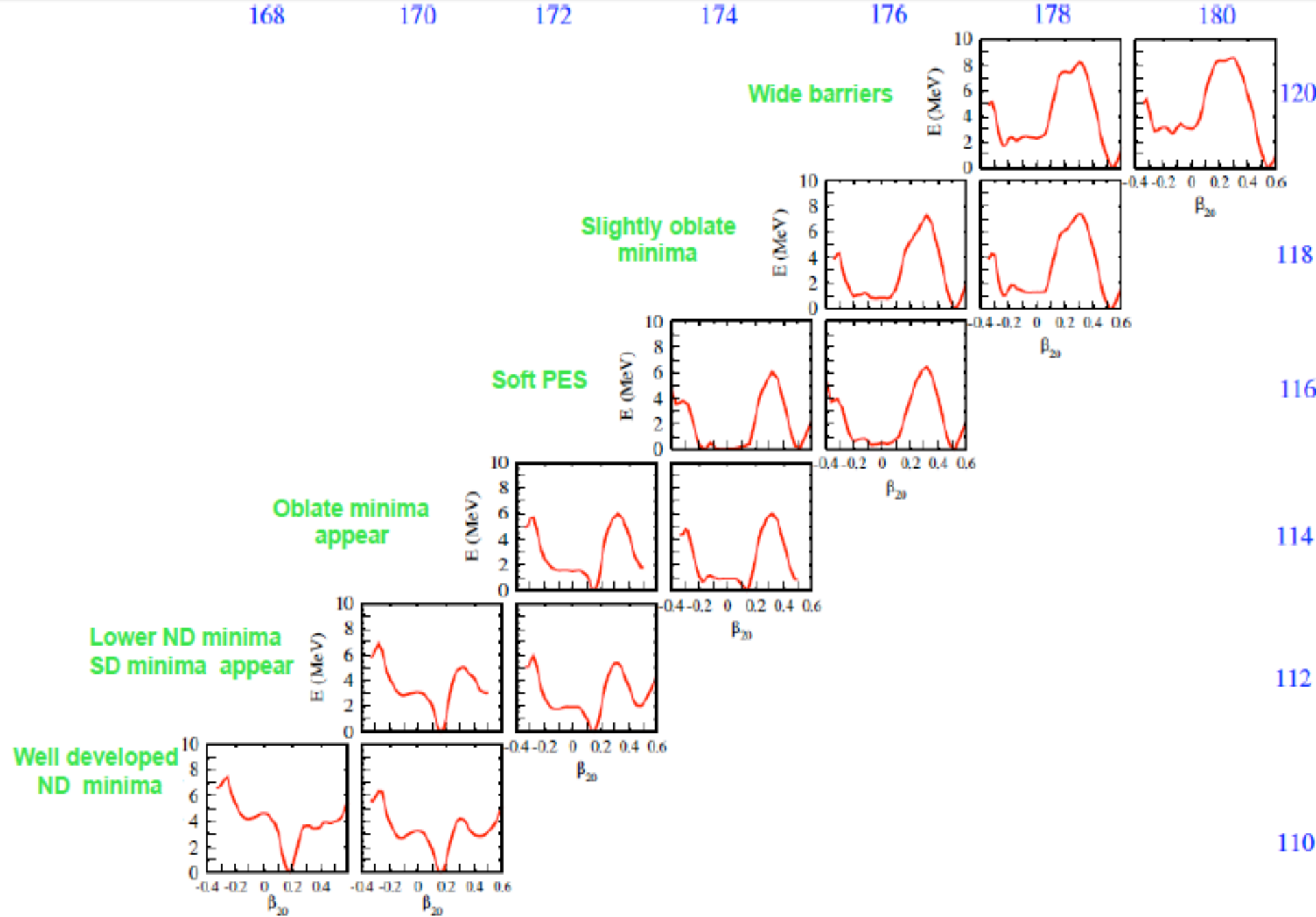
Decay chain of actinides

Same level of agreement with the Skyrme case

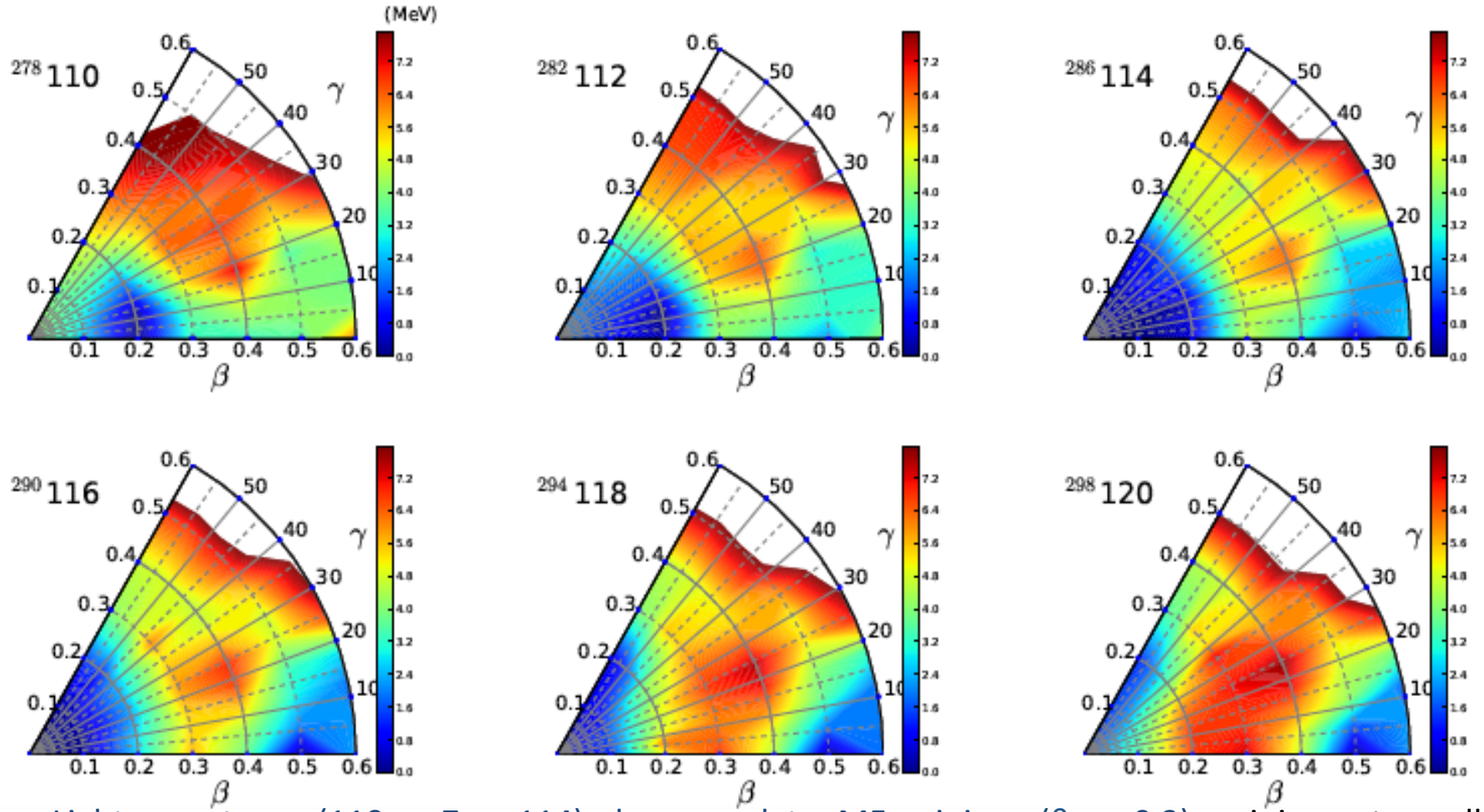




Shape transitions in superheavy nuclei

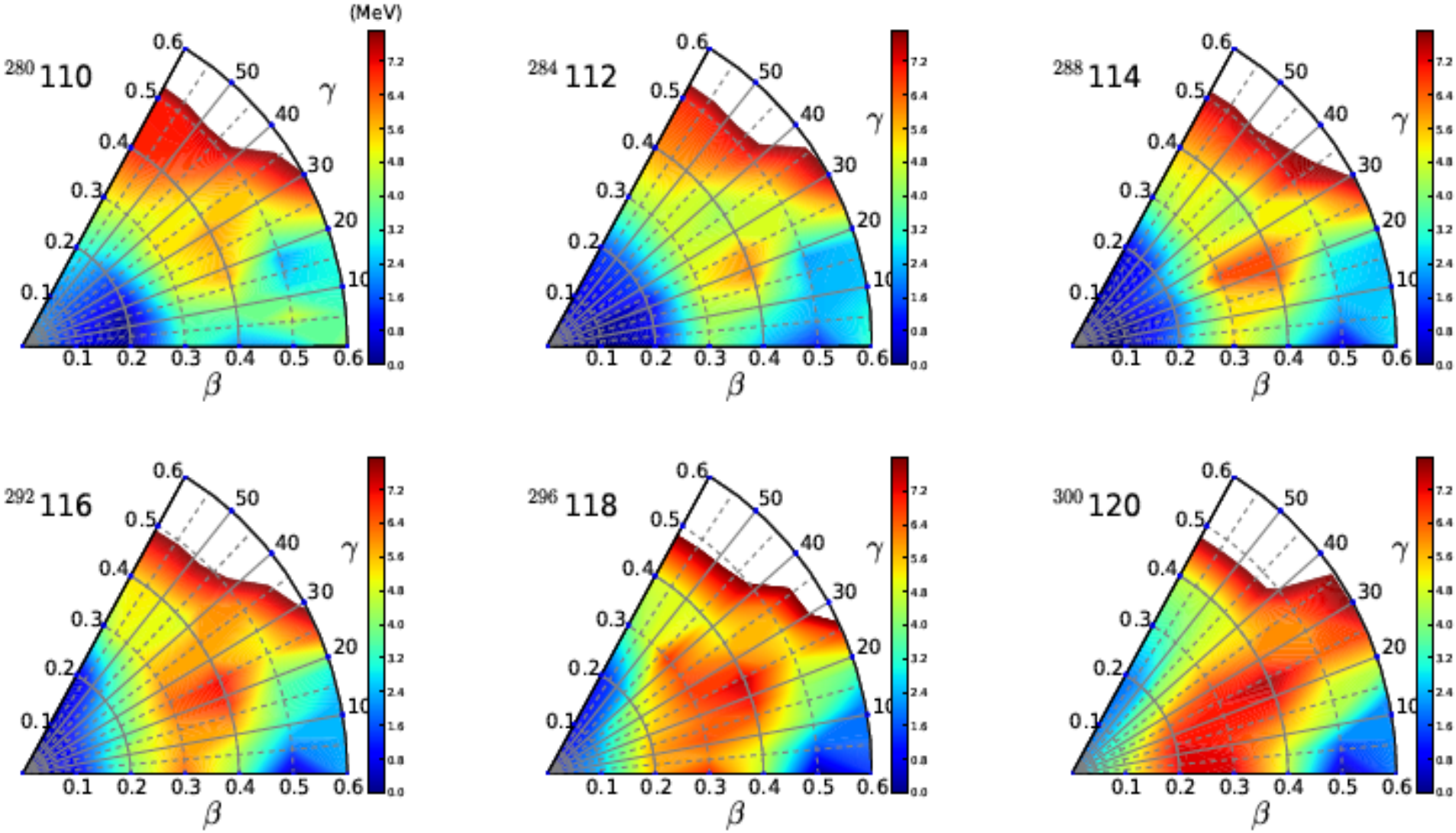


Triaxial shapes in the α-decay chain of $^{298}120$



- Lighter systems (110 < Z < 114) deep, prolate MF minima ($\beta_{20}\approx$ 0.2). minima at small quadrupole deformations.
- Heaviest systems (Z>118) soft oblate axial shapes with
- Intermediate nuclei (Z≈ 116) display both oblate and prolate minima that extend from the spherical configuration to $\beta_{20}\approx$0.3-0.4

Triaxial shapes in the α-decay chain of $^{300}120$



With increasing mass number: shift of the saddle point to smaller deformations and wider barriers.

Deep prolate minima at $\beta_{20} > 0.5$. The inclusion of reflection asymmetric shape degrees of freedom is expected to drastically reduce or remove completely the outer barrier.

α-decay chains of $^{298}120$ and $^{300}120$

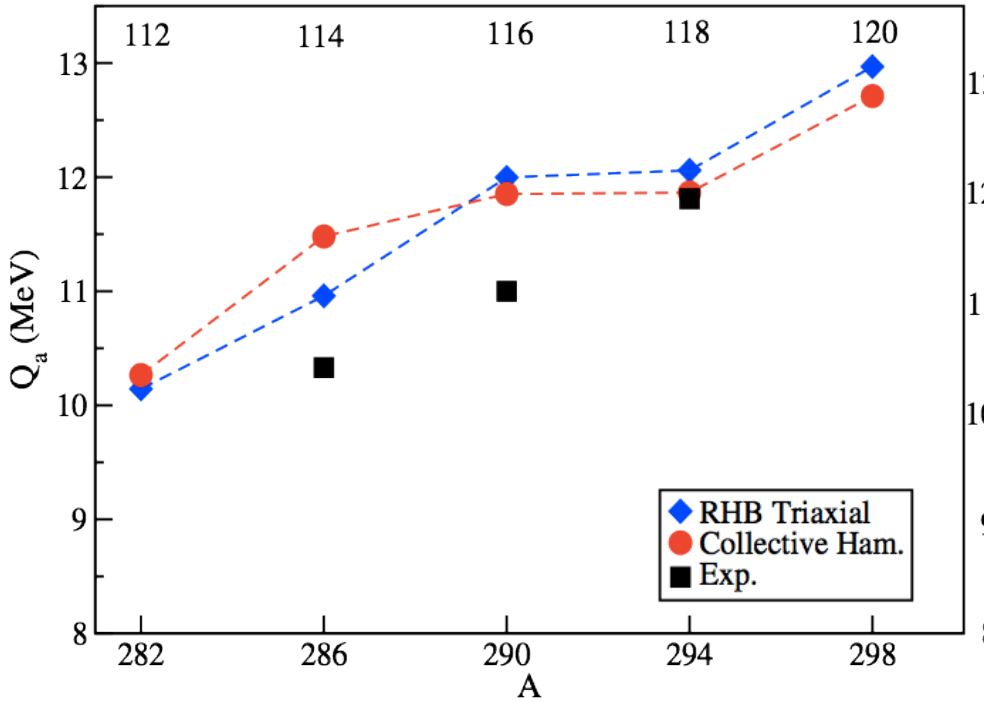
Red line: Q_α values computed for transitions $0^+ \rightarrow 0^+$ between eigenstates of the collective H.

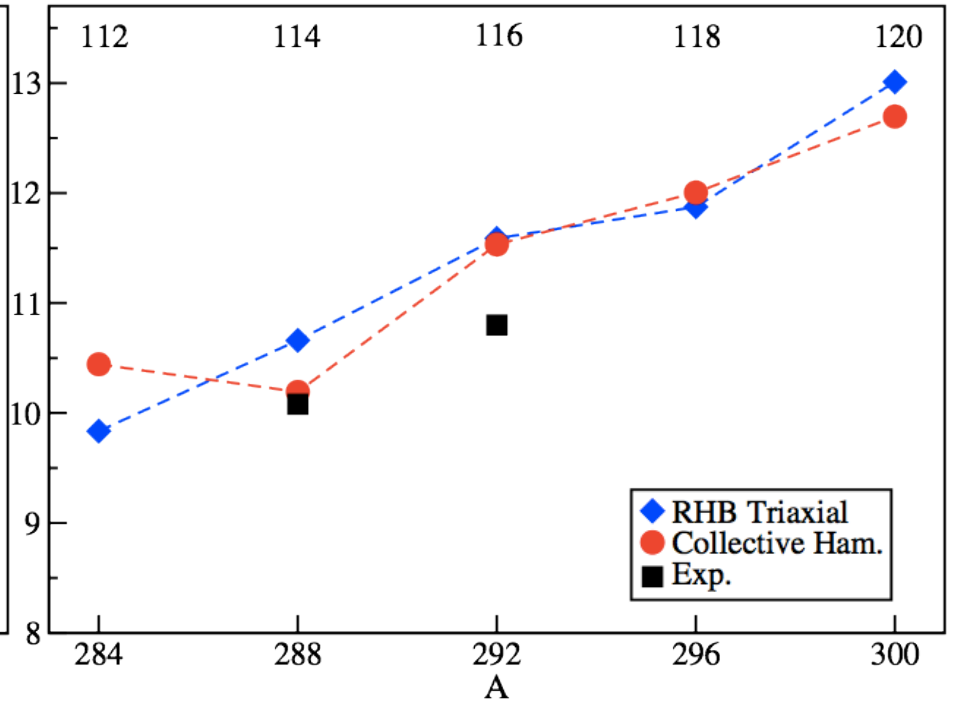
Differences with respect to MF values *are not large*, especially for the *heaviest, weakly oblate deformed or spherical systems*.

For the *lighter prolate and more deformed nuclei*, the differences can be *as large as* the deviations from experimental values.

α-decay chain of $^{298}120$

α-decay chain of $^{300}120$



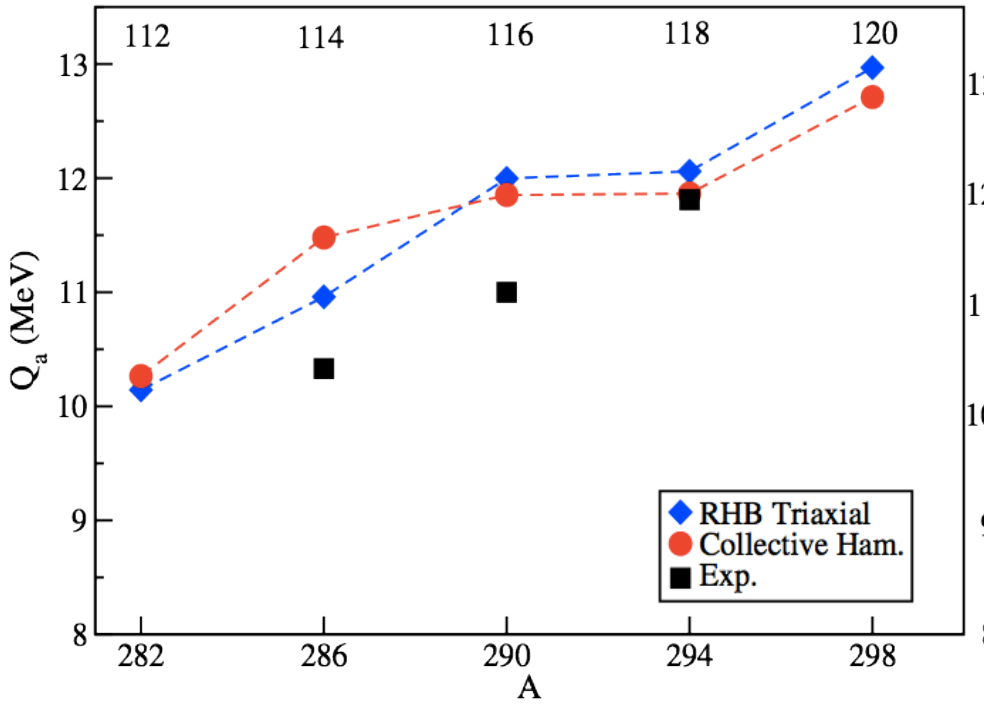


α-decay chains of $^{298}120$ and $^{300}120$

Identication of SHN by their -decay chains.

Blue line: Calculated Q_α for transitions between the self-consistent MF minima on the triaxial RHB energy surfaces.

α-decay chain of $^{298}120$



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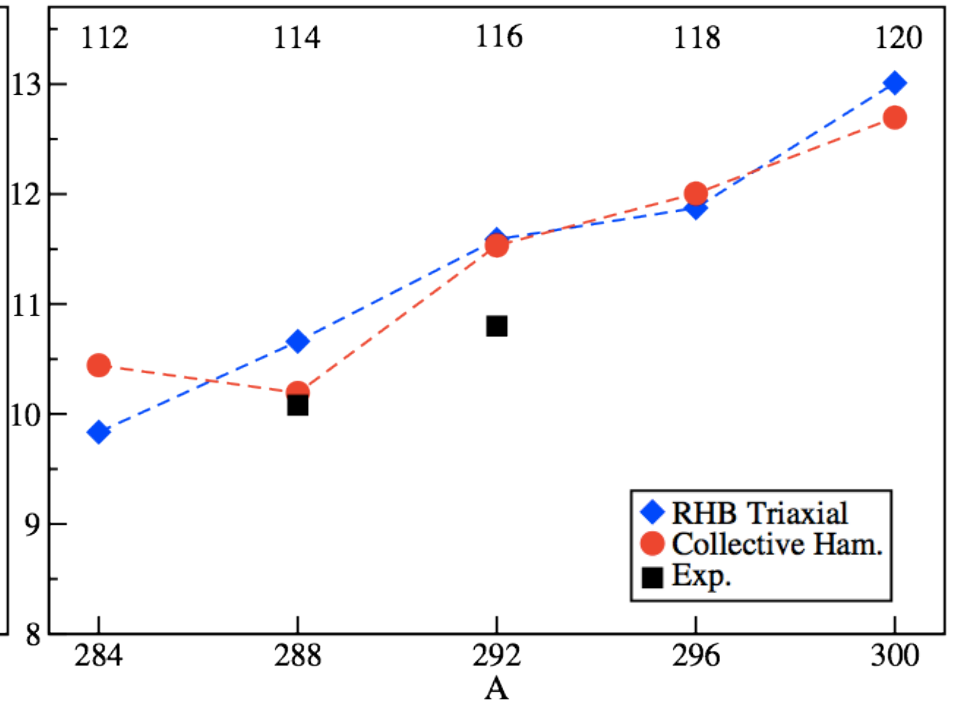
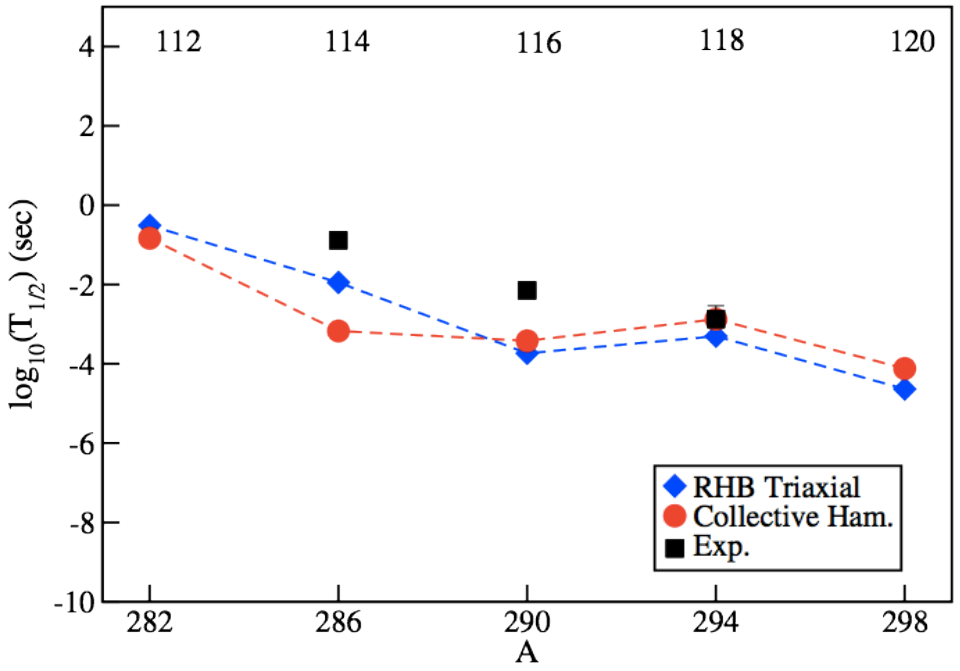


Half-lives in the α-decay chains of $^{298}120$ and $^{300}120$

Viola-Seaborg-Sobiczewski (VSS) formula

T_α for the decay chain of $^{298}120$



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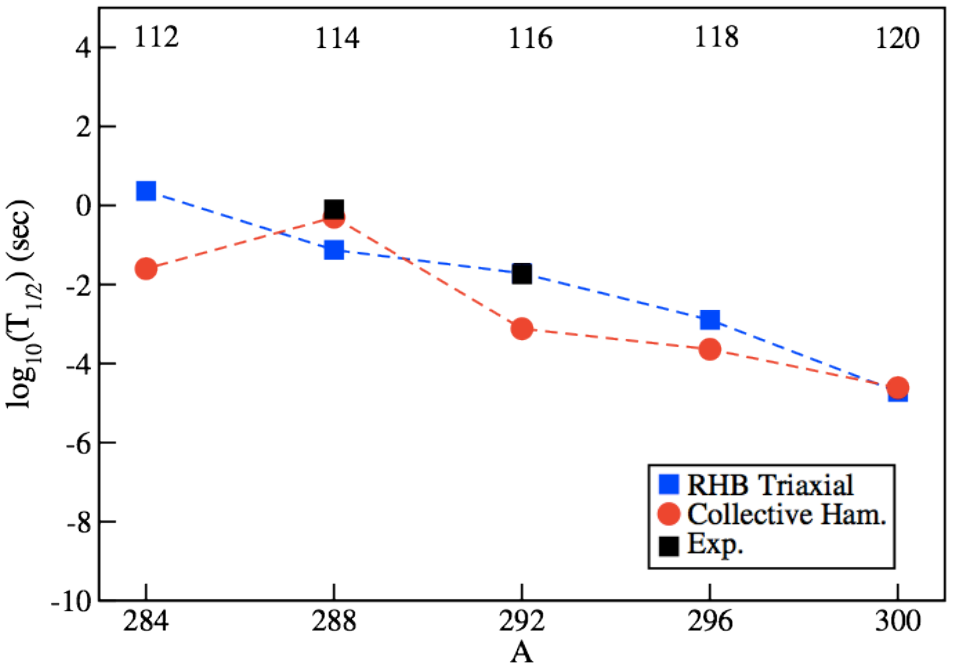
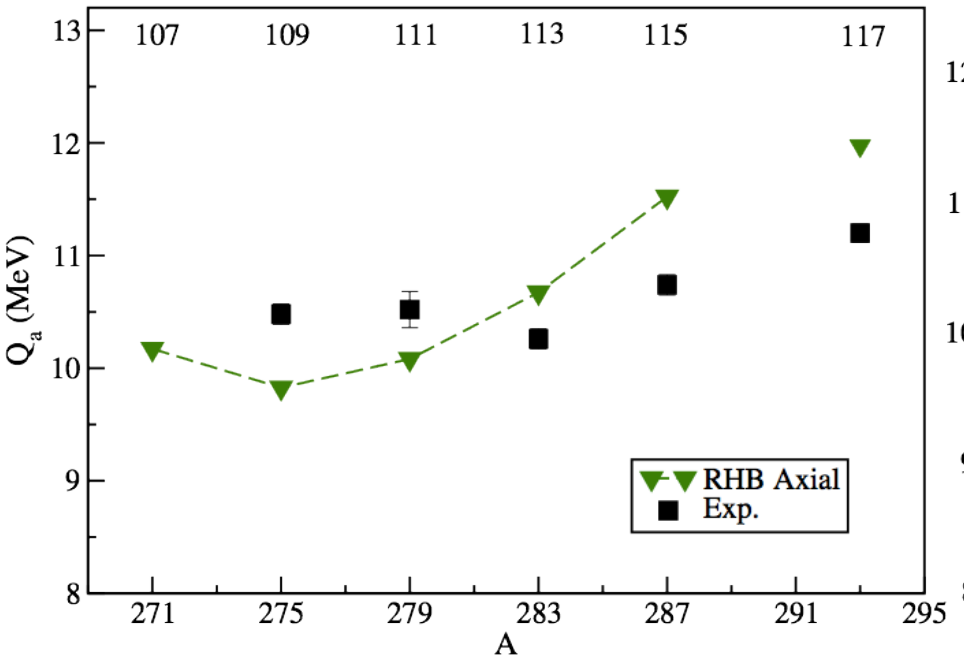


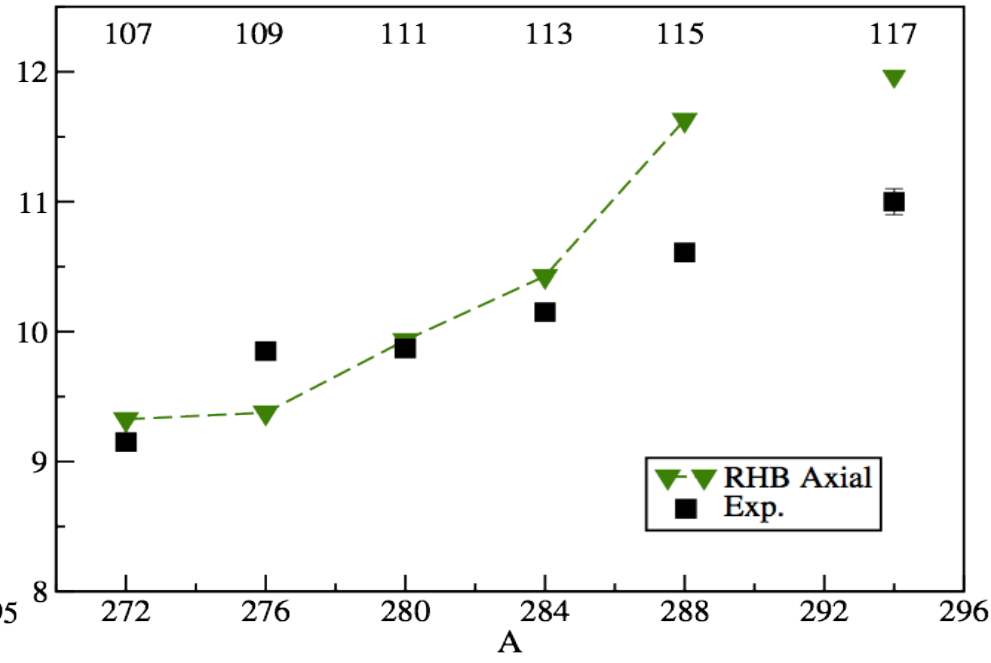
α-decay chains of $^{287}115$ and $^{288}115$

Blocking approximation for the odd particle

α-decay chain of $^{287}115$



α-decay chain of $^{288}115$



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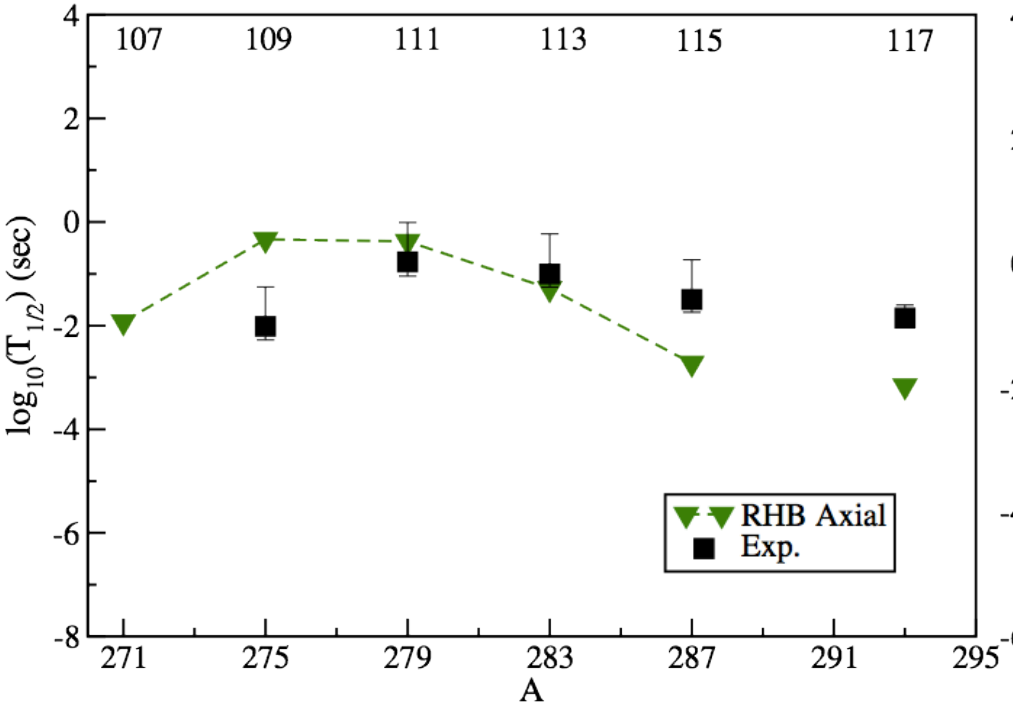

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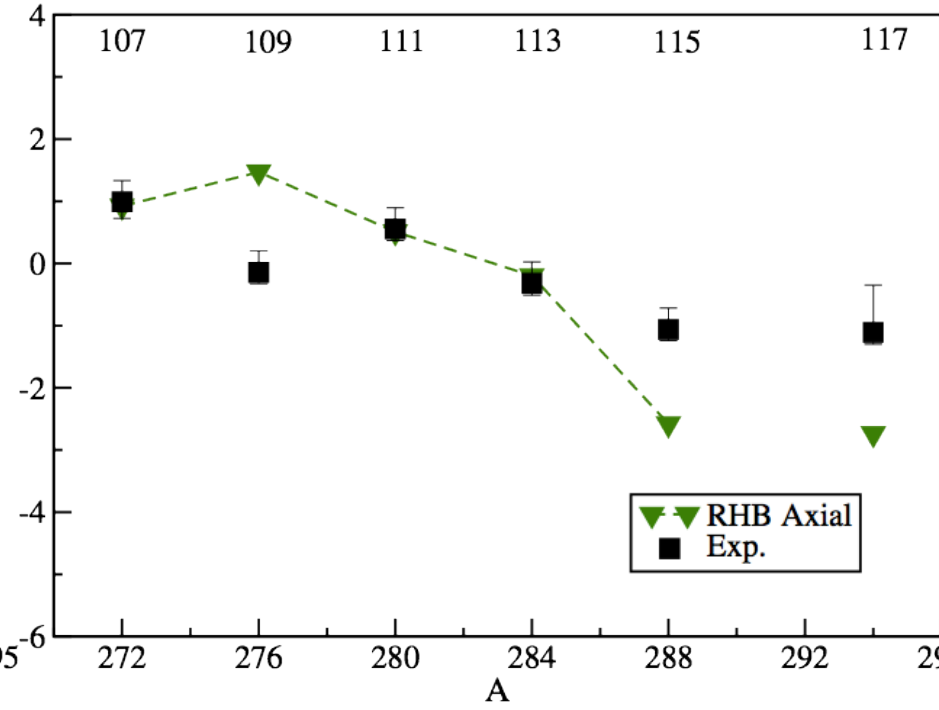


Five-dimensional collective Hamiltonian

... nuclear excitations determined by quadrupole vibrational and rotational degrees of freedom

$$H_{\rm coll} = \mathcal{T}_{\rm vib}(\beta,\gamma) + \mathcal{T}_{\rm rot}(\beta,\gamma,\Omega) + \mathcal{V}_{\rm coll}(\beta,\gamma)$$

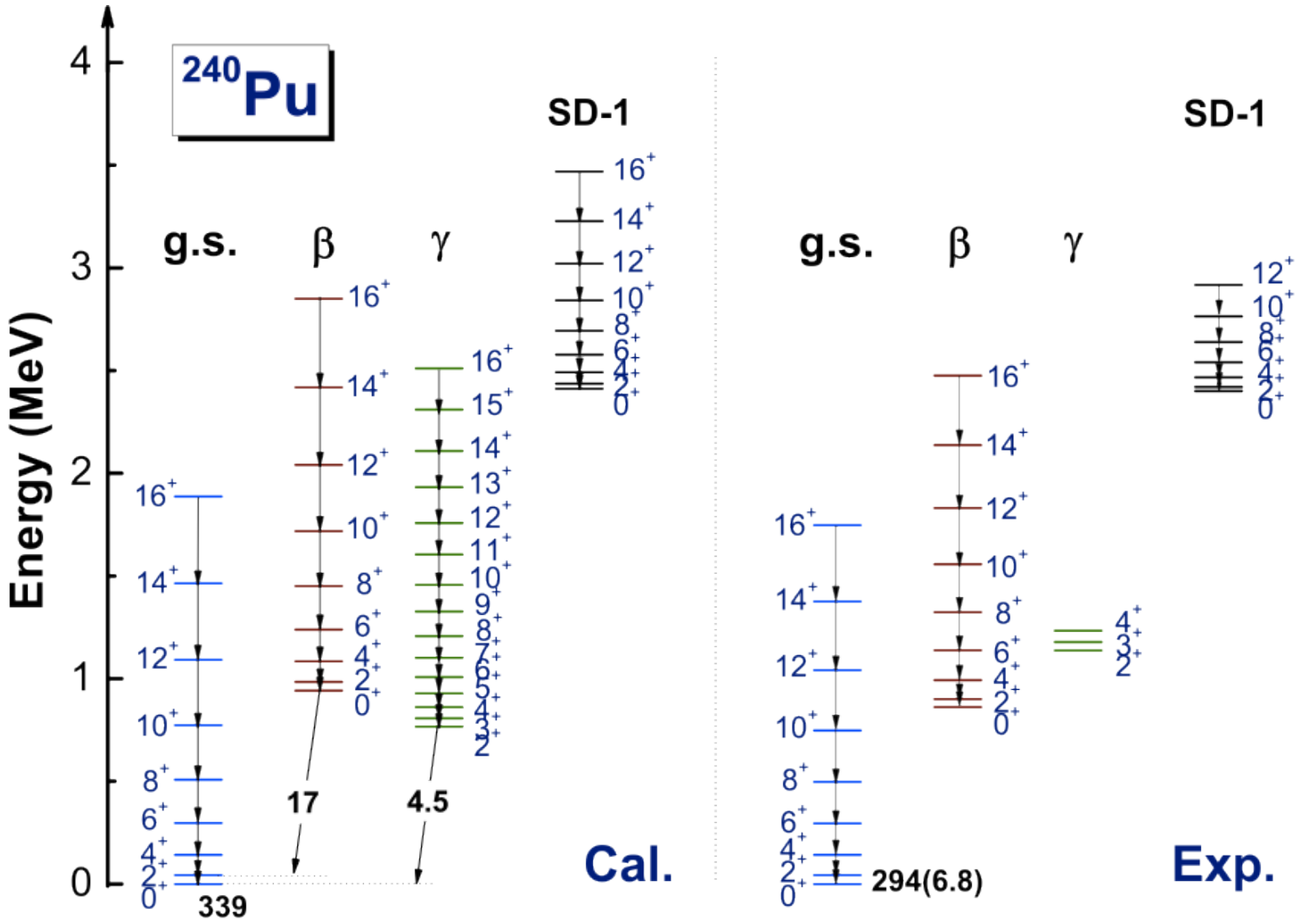
$$\mathcal{T}_{\rm vib} = \frac{1}{2}B_{\beta\beta}\dot{\beta}^2 + \beta B_{\beta\gamma}\dot{\beta}\dot{\gamma} + \frac{1}{2}\beta^2 B_{\gamma\gamma}\dot{\gamma}^2$$

$$\mathcal{T}_{\rm rot} = \frac{1}{2}\sum_{k=1}^{3}\mathcal{I}_k\omega_k^2$$

The entire dynamics of the collective Hamiltonian is governed by the seven functions of the intrinsic deformations β and γ: **the collective potential, the three mass parameters: $B_{\beta\beta}$, $B_{\beta\gamma}$, $B_{\gamma\gamma}$, and the three moments of inertia I_k.**

$E^{th}_{4^+_1}/E^{th}_{2^+_1} = 3.33$

$E^{exp}_{4^+_1}/E^{exp}_{2^+_1} = 3.31$



α-decay chains of $^{298}120$ and $^{300}120$

Blue line: Calculated Q_α for transitions between the self-consistent MF minima on the triaxial RHB energy surfaces.
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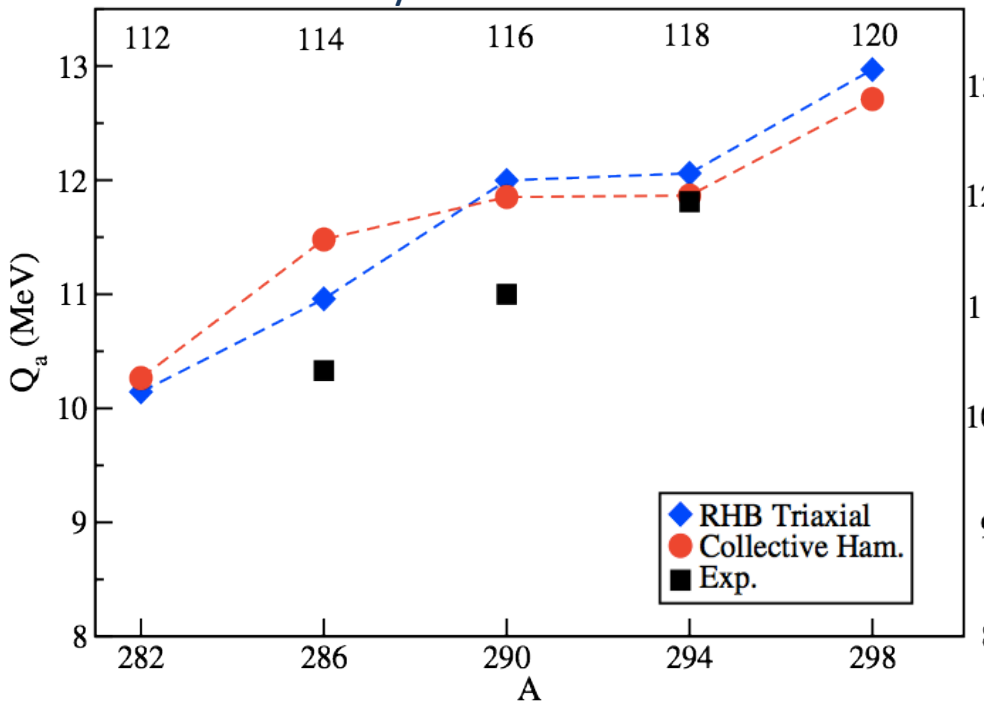
α-decay chain of $^{298}120$



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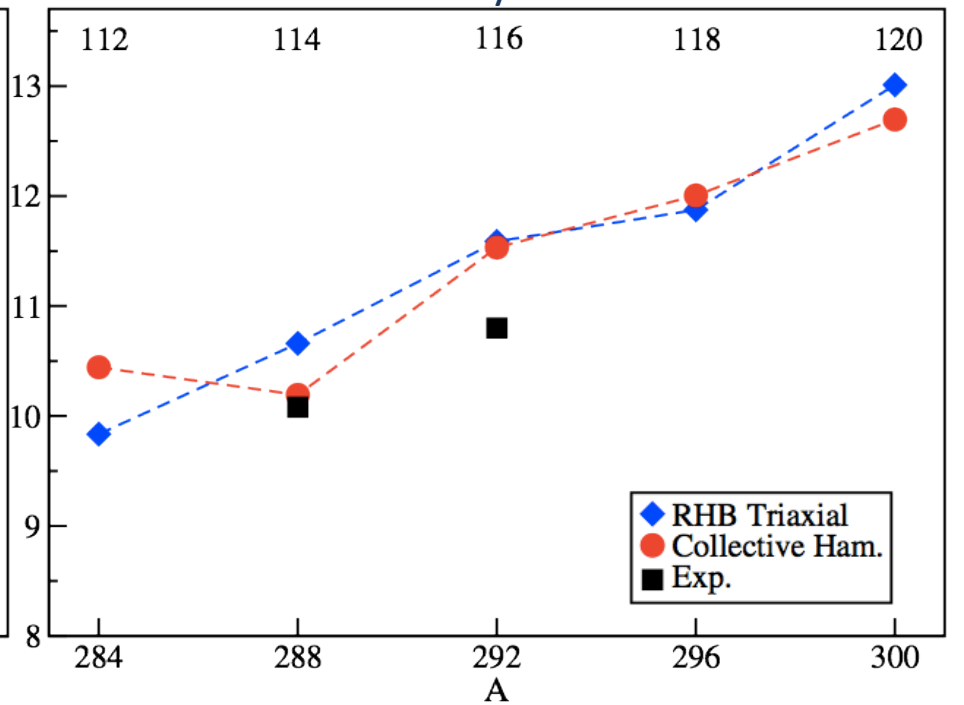

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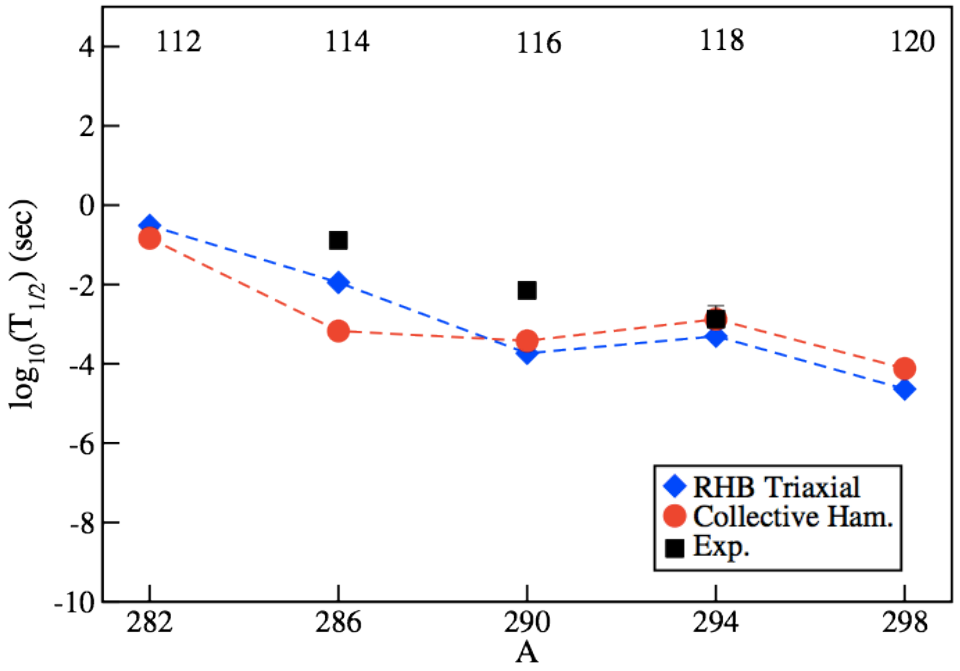

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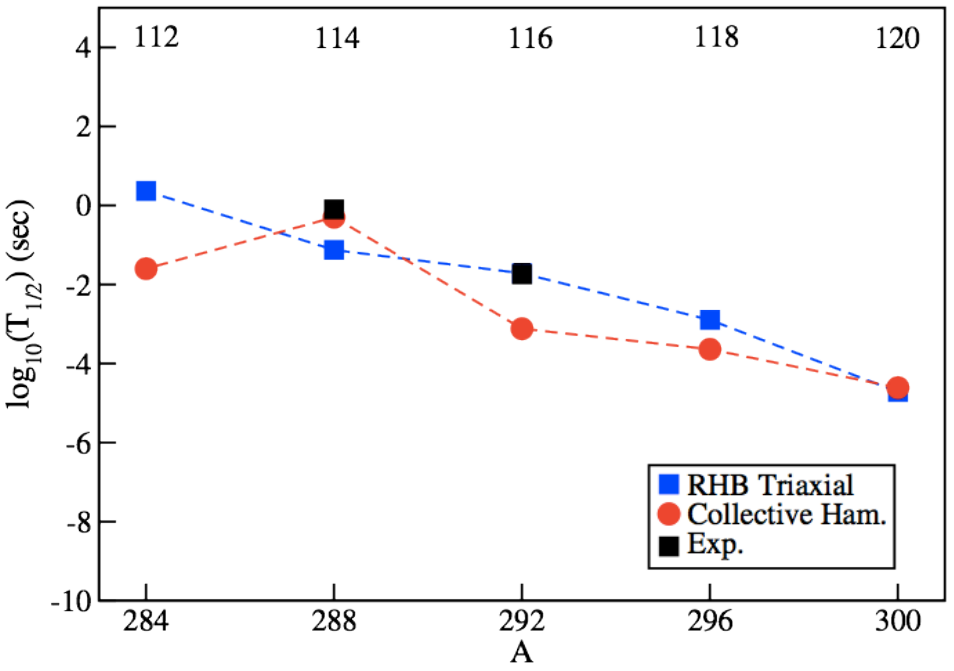

Summary:

The structure of actinides and SHNs has been analyzed using a self-consistent formalism based on NEDF.

Calculations of even-even, odd-even and odd-odd nuclei with Z > 90, using axial, reflection asymmetric and triaxial implementations of the RHB model and with a collective Bohr Hamiltonian, beyond the MF approximation.

Conclusions:

- *Potential energy surfaces* and *fission barriers* of actinides are well-reproduced.
- ***Normal Deformed and Super Deformed*** prolate minima appear in the binding energy surfaces of heaviest isotopes, which ***are crucial for their stability***.
- The calculated Qa-values and a-decay half-lives ($T_{1/2}$) are in agreement with available data.
- Beyond MF calculations are important for a quantitative description of α–decay chains in this mass region.

In collaboration with:

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and Dario Vretenar
PMF, University of Zagreb